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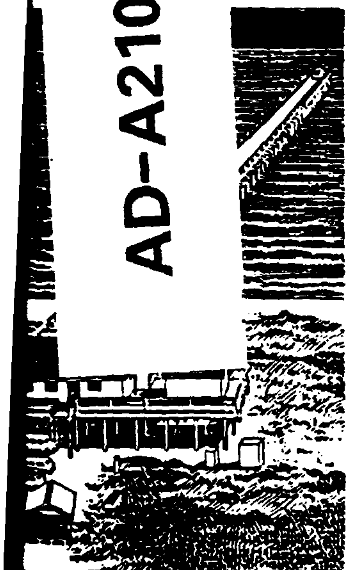

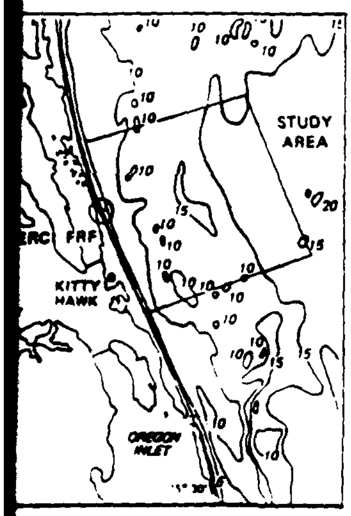

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PHYSIOGRAPHIC AND GEOLOGICAL SETTING OF THE COASTAL ENGINEERING RESEARCH CENTER'S FIELD RESEARCH FACILITY

by

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This report describes, in general terms, aspects of the regional and local geology of the Coastal Engineering Research Center's Field Research Facility (FRF) in Duck, North Carolina. The FRF is located on the Outer Banks which form the seaward margin of the Atlantic Coastal Plain province in this region. The beach and dunes of the barrier island at the site of the FRF are composed of fine to very coarse sand mixed with some granule and pebble-sized material. This lithology remains essentially unchanged beneath the barrier to a depth of more than 15.2 m (50 ft) below present sea level where finer grained sediments predominate. The inner continental shelf in the area is marked by irregular bottom topography with four large shoals interrupting seaward inclination of the shelf floor. The inner shelf is mantled by fine to very coarse sand with the coarser material occurring primarily on the shoals.

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PREFACE

The report herein was authorized as part of the Shore Protection and Restoration Program by the Office, Chief of Engineers (OCE), US Army Corps of Engineers. Research was conducted as a joint effort with the US Geological Survey under Barrier Island Sedimentation Studies Work Unit 31665 at the Coastal Engineering Center (CERC) of the US Army Engineer Waterways Experiment Station (WES). Messrs. John H. Lockhart, Jr., and John G. Housley were OCE Technical Monitors.

This report was prepared by Messrs. Edward P. Meisburger, Coastal Morphology Unit, Coastal Processes Branch (CR-P), Research Division (CR), CERC; S. Jeffres Williams, US Geological Survey; and Charles Judge (formerly of CERC) under direct supervision of Dr. Steven A. Hughes, former Chief, CR-P, and Mr. H. Lee Butler, Chief, CR. Chief and Assistant Chief of CERC were Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., respectively. Reviews were provided by Messrs. Peter Popenoe, and Ronald Circe, Ms. Elizabeth Winget of the US Geological Survey, and Dr. Suzette Kimball of CERC. This report was edited by Ms. Shirley A. J. Hanshaw, Information Products Division, Information Technology Laboratory, WES.

Acting Commander and Director of WES during report publication was LTC Jack R. Stephens, EN. Technical Director was Dr. Robert W. Whalin.

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PART I: INTRODUCTION

1. The US Army Engineer Waterways Experiment Station Coastal Engineering Research Center's (CERC's) Field Research Facility (FRF) is located near Duck on the Outer Banks of North Carolina approximately 8 km (12.9 miles) north of Kitty Hawk (Figure 1). This report presents background information on the FRF in a regional and site-specific context that may be of interest to users of the FRF.

2. The general area described in this report extends along the coast from Cape Henry, Virginia, at the entrance to Chesapeake Bay to Cape Lookout, North Carolina, and inland across the Coastal Plain Province to the Piedmont Province. Geology and geomorphology of the Coastal Plain Province is relatively simple in contrast to the complexities of the Piedmont Province and the Appalachian Highlands to the west.

3. This report does not provide an exhaustive review of the voluminous body of scientific literature on regional and local aspects of the FRF site. Rather, it presents selectively chosen references to generally illustrate pertinent factors of the environment.

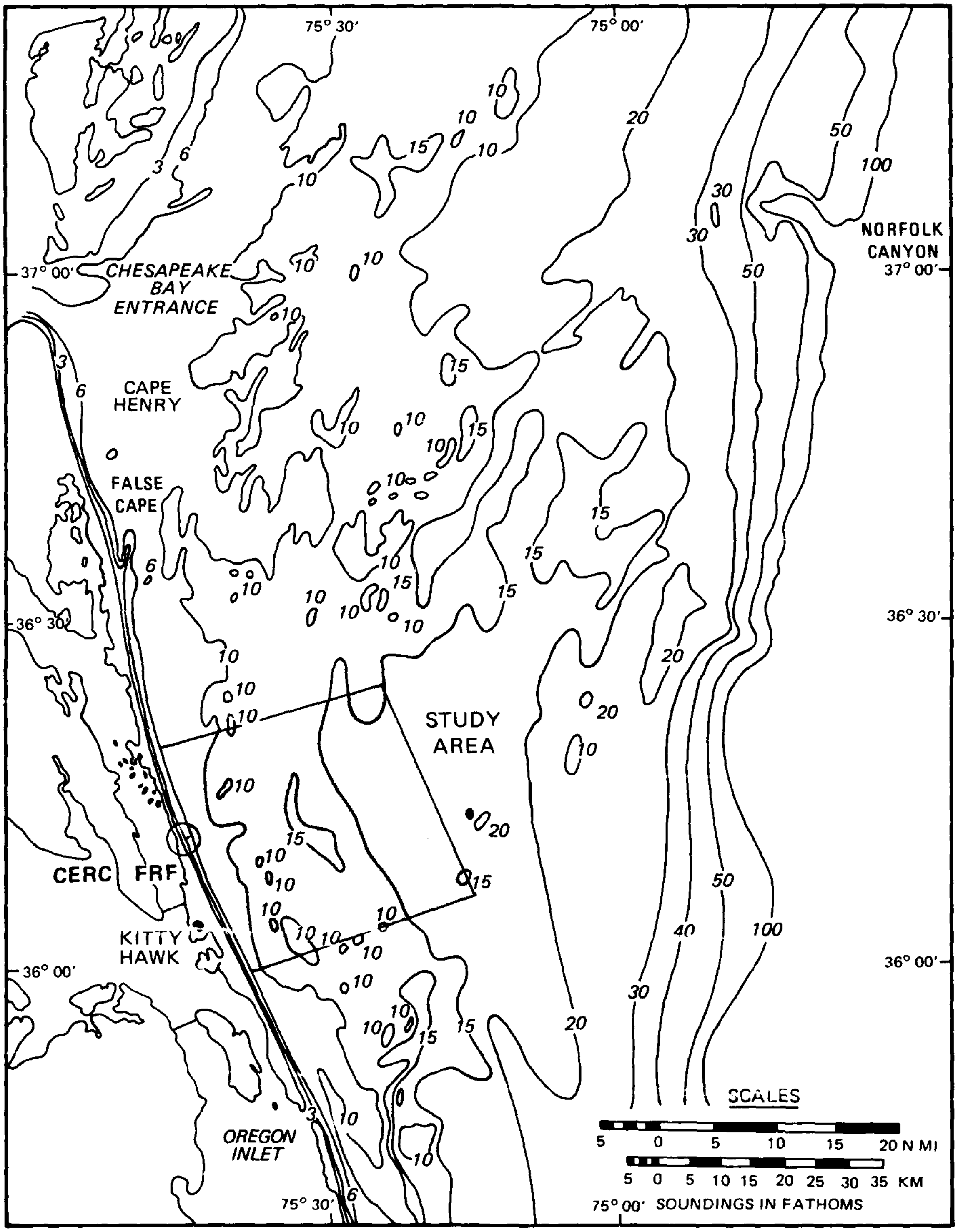

Figure 1. Location of CERC's FRF on the Outer Banks of North Carolina

PART II: REGIONAL PHYSIOGRAPHY AND GEOLOGY

Physiography

4. The Outer Banks form the easternmost edge of the Coastal Plain province. They consist of a series of narrow, sandy barrier islands extending southeast from near Cape Henry, Virginia, in a slightly convex seaward manner to Cape Hatteras, North Carolina, then trend southwestward in a concave-seaward arc to Cape Lookout, North Carolina (Figure 1). South of Cape Lookout the barrier chain continues to Cape Fear near Wilmington, North Carolina. The islands along this latter reach are closer to the mainland, separated in most places only by a narrow channel.

5. The Outer Banks are backed by extensive shallow sounds which are connected to the Atlantic Ocean by a few tidal inlets separating the barrier into a chain of islands. Currituck Sound, the northernmost sound, backs the barrier chain in the general vicinity of the FRF. It is comparatively narrow; however, it is extended to the west by another shallow body of water, the east-west trending Albemarle Sound. South of Currituck Sound are two small sounds--Roanoke and Croatan--separated by Roanoke Island. South of these bodies of water lies the wide, shallow Pamlico Sound which backs the Outer Banks to Cape Lookout.

6. West of the sounds backing the Outer Banks, the coastal plain remains low-lying, and much of the region is covered by extensive swamps and lakes. The main topographic features of the plain are a series of north-south trending terraces which rise in a stepwise fashion westward and mark former shorelines corresponding to higher sea level stands during the Pleistocene.

7. The Piedmont Province lies between the Coastal Plain on the east and the Blue Ridge Mountains to the west. The eastern boundary of the Piedmont lies along the fall line where a relatively abrupt change in elevation occurs as more resistant crystalline rocks of the Piedmont give way to softer Coastal Plain sediments. The Piedmont is an ancient erosion surface characterized by rolling hills with some high standing remnants of more resistant rock.

Geology

Coastal Plain and Piedmont Province

8. Barrier and back barrier deposits of the Outer Banks are composed of Holocene and Pleistocene material. In places, Pleistocene elements form

headlands and ridge and swale features. West of the sounds, the eastern half of the Coastal Plain is underlain by Quaternary deposits which unconformably overlie late Tertiary sediments (Figure 2). In the western part of the

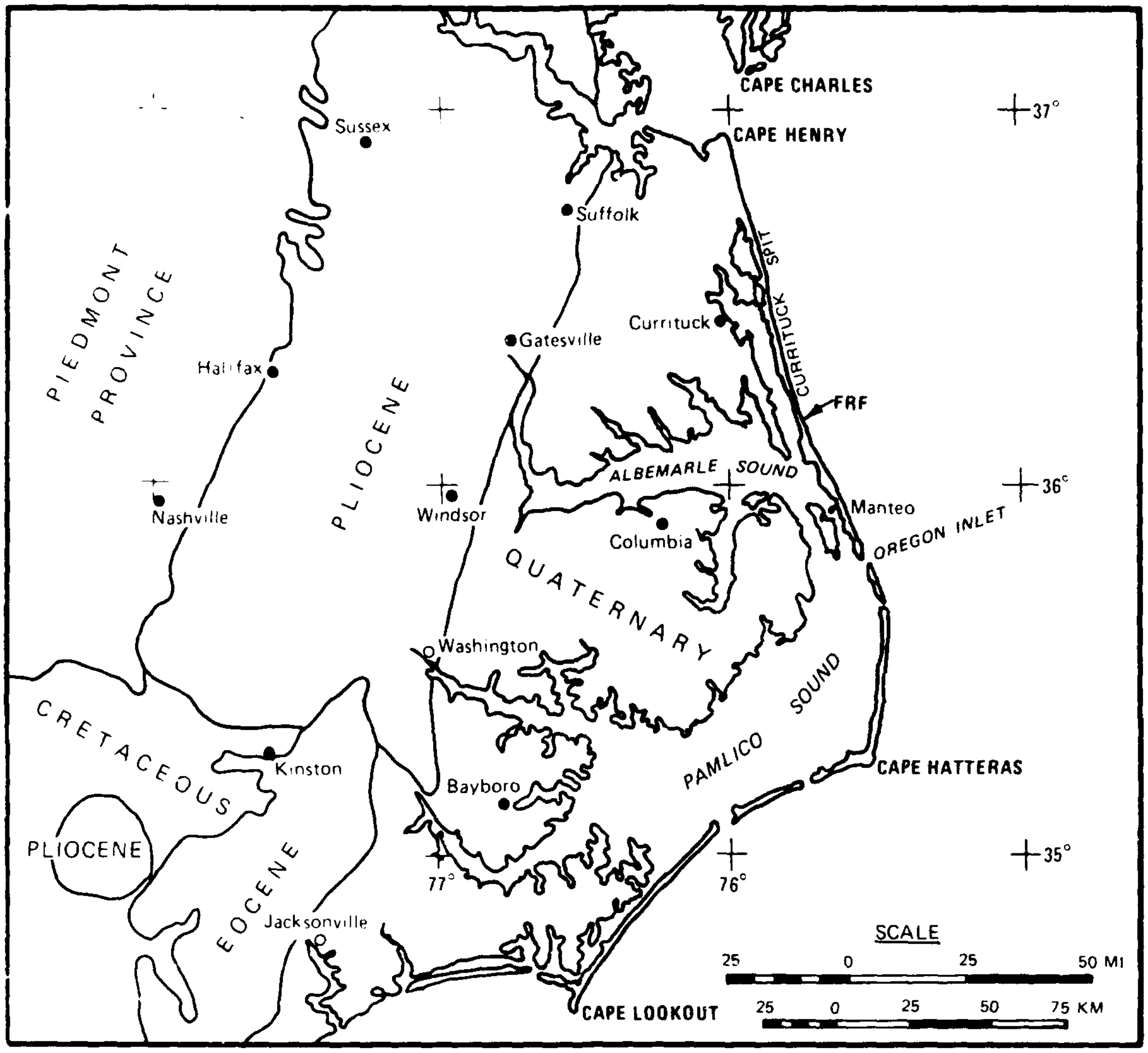

Figure 2. Generalized geology of the coastal plain in the area of the Outer Banks

Coastal Plain the Yorktown Formation, which based on recent studies is probably of Pliocene age (Gibson 1983), outcrops in the northern two-thirds of the area. In the southern third, the Eocene Castle Hayne Formation occupies most of the eastern part of the plain. Cretaceous rocks, largely of the Pedee and Black Creek Formations and an outlier of the Yorktown Formation, occupy the western part of the plain.

9. The Piedmont Province is underlain mostly by metamorphosed rocks of late Precambrian and early Paleozoic age and by intrusive rocks that range

from gabbro to granite. Geologically, the Piedmont Province is much more complex than the Coastal Plain because of greater variety of rock types and ages, metamorphism, folding, and extensive faulting. It is probable that the Piedmont Province in North Carolina and contiguous areas to the north are the ultimate source of sediments forming the Outer Banks barriers.

Origin and evolution of Outer Banks barriers

10. A number of theories have been advanced to explain the origin of barrier islands. Early theories were proposed by de Beaumont (1845), who suggests that barrier islands formed from the upward building of offshore bars, and by Gilbert (1885), who attributed barriers to longshore drift forming spits downdrift of headlands. These spits were subsequently segmented by inlet formation, thus forming discrete barrier islands.

11. More recent theories of barrier island origin include that of Hoyt (1967) who proposed that rising sea level and/or land submergence would flood areas landward of mainland beaches leaving the higher dunes and beach ridges, now isolated from the mainland shore, so that they formed early barrier islands. Fisher (1968) also considered submergence responsible for barrier island formation but believed, as did Gilbert (1885), that they originated as complex spit chains during submergence. Based on evidence from gulf coast barriers, Otvos (1970) concluded that accretion of submerged shoal areas (similar to de Beaumont's (1845) theory) accounted for the origin of a number of barriers along the gulf coast.

12. Schwartz (1971) reviewed the main theories of barrier island formation and concluded that there was growing evidence that all the primary modes of initiation occurred at certain times and places in the past. He proposed a tentative classification recognizing these main theories as valid.

13. Field and Duane (1976) presented evidence that many if not most barrier islands, especially those in the mid-Atlantic region, had initially formed well seaward of the present coast during the Holocene transgression and had migrated to their present location in response to rising sea level. Because these barriers have evolved and assumed new characteristics during and subsequent to their migration across the shelf, the authors concluded that mode of initial formation was of less consequence than their history of evolution since evolutionary trends can be used to predict future changes.

14. The origin of Outer Banks barrier islands has been studied by

several investigators, including Pierce and Colquhoun (1970) who studied a section extending from near Kitty Hawk about 8 km south of the FRF to Cape Lookout. They found that during the Holocene transgression a barrier initially formed by flooding, in the manner described by Hoyt (1967). The primary barrier had apparently reoccupied one formed during a stillstand of the Wisconsinan regression. The Outer Banks as known today then developed from the initial barriers by retreat and migration of headlands and the formation of younger barriers as a result of spit elongation and segmentation.

15. Moslow and Heron (1979) interpreted the depositional environment and Quaternary evolution of Core Banks at the southern end of the Outer Banks barrier chain. They concluded that Core Banks probably originated about 15,000 years ago either as an elongated spit or as a result of mainland beach detachment. The barrier migrated landward in response to rising sea level until about 4,000 years ago when sea level rise abated considerably. Subsequent inlet formation and migration have had a dominant influence in the further development of Core Banks.

<u>Recent evolution of
Outer Banks barriers</u>

16. The modern development of the Outer Banks and Cape Henry headland (Figure 1) from 12 km west of Cape Henry to 8 km west of Cape Hatteras was investigated by Everts, Battley, and Gibson (1983). Using historical maps and charts surveyed between 1852 and 1980, they plotted and analyzed shoreline changes for the oceanside and soundside of the barrier islands.

17. The authors found that during the 1852 to 1980 time period, 68 percent of the ocean shoreline in the study area retreated, 28 percent prograded, and 4 percent remained stable. The average rate of retreat of the ocean shoreline between Cape Henry and Cape Hatteras was 0.8 m (2.6 ft) per year. The landward shoreline of the barrier islands also retreated (moved seaward) at an average rate of 0.1 m (0.34 ft) per year.

18. Ocean-side and sound-side shoreline retreat has resulted in an average narrowing of the islands at a rate of 0.9 m (3.0 ft) per year between 1852 and 1980. Everts, Battley, and Gibson (1983) point out that this process is contrary to the classic barrier migration process in which the ocean shoreline retreats, while overwash and inlet depositional processes cause the soundside shoreline to prograde (i.e. move landward). Because the islands are presently too wide to enable overwash sediments to be carried to the sound, most

existing sound-side progradation is associated with inlets. Continued island narrowing will eventually allow overwash to reach the sound side and initiate a cycle of landward migration; however, this is not likely to occur in the near future.

PART III: HISTORICAL DEVELOPMENT OF FRF SITE

Barrier Stratigraphy

19. In conjunction with design of the FRF in 1972, a number of cores and borings were obtained to investigate foundation conditions along the site of the proposed FRF research pier. Megascopic descriptions and size characteristics of samples from these cores and borings were compiled in an informal letter.* Three peat samples were encountered in the cores and borings, and these were later dated for use in a study of Quaternary sea level history of the Atlantic coast (Field et al. 1979). Meisburger and Williams (1987) analyzed samples from the cores and borings and, from these and seismic reflection data, obtained information on the general stratigraphy and historical development of the FRF site.

20. Five engineering borings and four nearshore vibracores were taken during the 1972 site investigation. All cores and Borings D1, D2, and D3 were situated along the alignment of the FRF (Figure 3); Borings D4 and D5 were made approximately 91.4 m (300 ft) south and north of the pier. Onshore borings were made with standard soil boring equipment with nearly continuous samples being taken as the hole advanced. Offshore cores were obtained using a vibrating coring apparatus having a tube diameter of 7.6 cm (3 in.) and a length of 6.1 m (20 ft).

Sediment units

21. Meisburger and Williams (1987) found four primary units of unconsolidated sediment in the borings and cores at the FRF. Because of similarity to units described by Shideler et al. (1972) on the Virginia shelf, tentative correlations were made between these units and Shideler's Units B, C, D, and E. Unit A of Shideler et al. (1972), if present under the FRF, lies below the maximum depth reached by the borings.

22. Sediment samples from the various units were analyzed to determine their primary and secondary components. The primary component was quartz. Secondary components consisted of granule- and pebble-sized rock fragments, heavy minerals, mica, glauconite pellets, mollusk shells, and foraminiferal

* Informal letter written to the author by Dr. Michael Field in 1973. He is currently with the US Geological Survey.

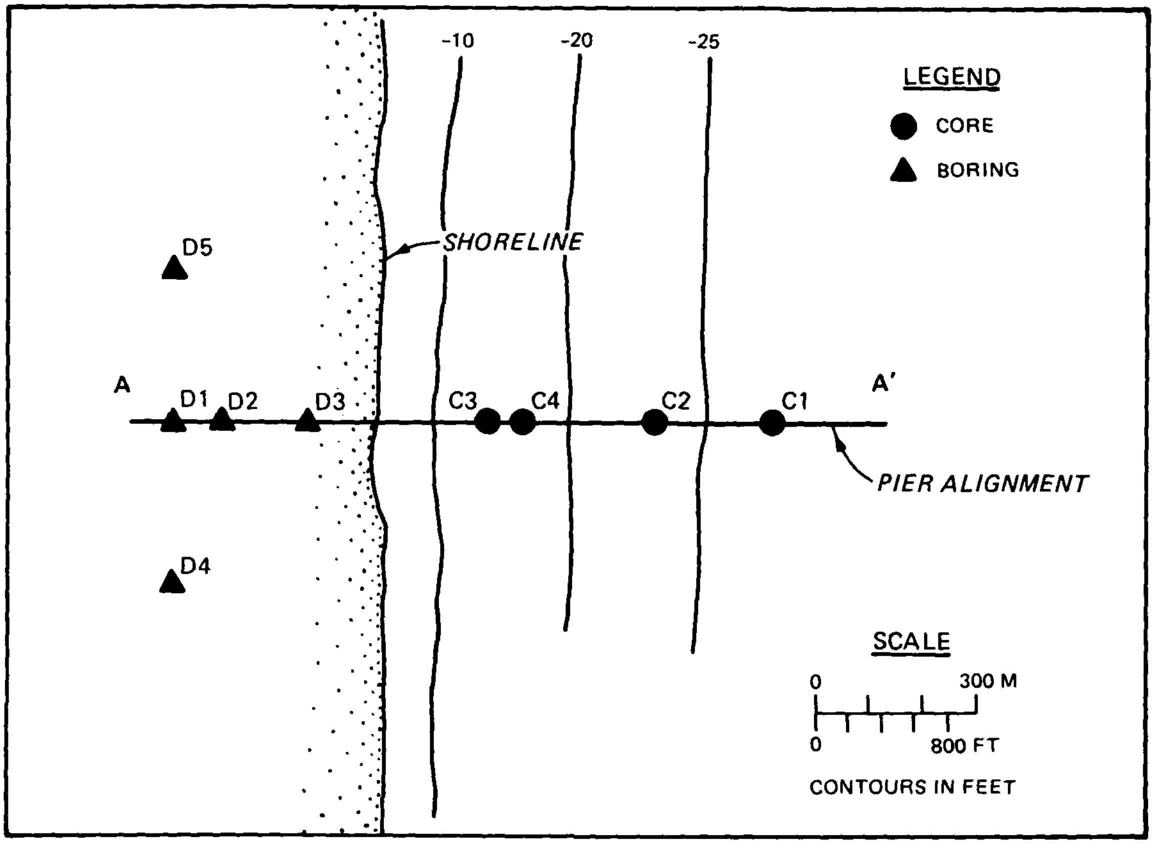

Figure 3. Location of borings and cores at the FRF site

tests. These components were useful in identifying and correlating the sediment units and for information on the depositional environment.

23. Unit B. Unit B is the lowermost deposit penetrated by the cores and borings. It consists of gray (Munsell 10YR6/1),* silty medium to coarse sand that is devoid of shell fragments, foraminifera, and other faunal debris. Glauconite pellets and mica occur, but both are relatively sparse (Table 1). In most samples silt is present in considerable quantity, but some intervals are silt free.

24. Sand peat layers occur in three of the borings (1, 3, 5) and in one offshore core (1). These deposits occur at the top of Unit B in all but one case, Boring D3, where the peat lies within the unit. The peat samples were

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* Code from "Munsell Soil Color Chart," Munsell Color Company, Baltimore, Maryland, 1954.

Table 1

Percent Frequency of Heavy Minerals in Borings and Cores

Minerals, %	Unit B	Unit C	Unit D	Unit E
Zircon	0.11	0.04	--	0.10
Rutile	0.49	0.11	--	0.24
Garnet	5.91	11.38	6.57	12.77
Staurolite	7.17	3.11	2.87	4.15
Kyanite	0.41	0.32	0.24	0.28
Epidote	24.82	10.48	8.33	10.77
Hypersthene	0.19	0.23	0.17	0.80
Sillimanite	0.40	0.12	0.42	0.51
Amphibole	37.96	5.60	74.40	56.89
Tourmaline	3.38	3.45	3.67	5.39
Black Opaque	18.82	13.81	3.22	7.26
Glauconite/C.15 gm	2.90	11.60	56.00	13.80
Mica/0.15 gm	5.00	156.90	53.20	1.80
No. of samples	14	16	10	30

radiocarbon dated, and results were published in Field et al. 1979. The data for these samples are as follows:

Hole	Depth Below msl*	Date, Years BP
Core 1	27.6 m (90.6 ft)	37,000
Boring D1	21.6 m (70.9 ft)	28,000
Boring D3	21.6 m (70.9 ft)	32,000
Boring D5	19.7 m (64.5 ft)	not dated

* msl = mean sea level

The environment of deposition of the peat was determined by pollen analysis in Boring D3 and was found to be nonmarine.

25. Unit B appears to have been deposited under different circumstances from the other units, as evidenced by the significantly higher epidote fraction and lower percentage of glauconite and amphibole (Table 1). Amphiboles are especially responsive to selective sorting processes perhaps as a result of the flattened shape that is characteristic of cleavage fragments. Epidote and glauconite, however, are less responsive to selective sorting, suggesting that Unit B sediments may be at least partially derived from different sources than the other units. Additionally, there is an absence of the calcareous

fragments (i.e., mollusk shells, foraminifera tests) that commonly occur in the other units suggesting that the deposit is of nonmarine origin or that leaching occurred during subaerial exposure after deposition.

26. Unit C. Unit C is a distinctive pinkish gray (Munsell 7.5YR6/2), silty, very fine sand containing mollusk shells, foraminifera tests, glauconite, and a large mica fraction. Layers of well-sorted medium to coarse sand occasionally occur in this unit. Mollusk shells, abundant in places, are generally from the small pelecypod *Mulinia lateralis* (Say), indicative of marginal marine waters. Shells of the gastropod *Nassarius trivitatus* (Say) occur rarely. *Elphidium excavatum* (Terquem) dominates the foraminiferal fauna, with secondary occurrences *Quinqueloculina seminula* (Linné) (Table 2).

27. Unit C can be distinguished from other units by its distinctive color and fine texture and its abundance of mica, both indicative of a low-energy depositional environment. Foraminifera and mollusk species are characteristic of marginal marine waters, commonly backbarrier lagoon, marsh, and tidal channel environments. Deposition of Unit C took place at some time

Table 2

Percent Frequency of Foraminifera in Borings and Cores

Species	Unit C	Unit D	Unit E
Ammonia beccarii (Linné)	tr*	tr*	tr*
Buccella hannai (Phleger & Parker)	0.5	1.0	0.3
Cibicides lobatulus (Walker & Jacob)		0.4	
Elphidium excavatum (Terquem)	94.1	91.7	91.5
Elphidium galvestonense (Kornfeld)		0.1	
Elphidium mexicanum (Kornfeld)	tr*	1.3	1.1
Eponides repandus (Fichtel & Moll)	0.4		
Guttulina sp.	tr*	0.8	0.3
Hanzawaia concentrica (Cushman)	tr*	2.7	4.7
Haynesina germanica (Ehrenberg)	0.9	0.4	tr*
Nonionella atlantica Cushman	tr*	0.5	2.0
Poroeponides lateralis (Terquem)	0.1		
Quinqueloculina seminula (Linné)	2.9	0.5	
Quinqueloculina jugosa Cushman	0.2		
Rosalina globularis D'Orbigny	0.8	0.3	
Webbinella concava Williamson	tr*	tr*	
No. of samples	29	10	14

* tr = present in quantities less than 0.10%.

after the underlying peat deposits which are dated at 28,000 years BP or earlier. If Unit C deposition occurred during the Holocene transgression, it probably took place about 7,000 to 8,000 years BP when eustatic sea level stood at approximately the level of the deposit.

28. Unit D. Unit D, representing the typical shoreface deposit, is a uniform gray (Munsell 10YR7/1) fine sand containing foraminifera and mollusk shells. Glauconite content of sediments in this unit is several times higher than in any of the other units. Gravelly sand layers containing granules and pebble size material are common. Foraminiferal fauna is more diverse than in Unit B but is also dominated by *E. excavatum* (Terquem). Important secondary species are *Elphidium mexicanum* (Kornfeld) and *Hanzawaia concentrica* (Cushman).

29. Unit D is also characterized by a relatively high content of glauconite pellets and amphibole. Because amphiboles may be expected to show relatively large frequency variations that are not source related but are the product of selective sorting, the large amount of this mineral type may be indicative only of a comparatively low-energy depositional environment.

30. Glauconite concentration is indicative of some factor other than selective sorting. It is possible that glauconite pellets are formed in place in the shoreface environment; however, the continental shelf floor off the FRF contains considerable amounts of glauconite pellets (Meisburger and Williams 1987) and could be a source for detrital pellets in Unit D. In the latter case, onshore drift of fine sediments winnowed from the shelf floor may be an important source for the shoreface fine sands. Onshore drift is suggested by the occurrence of *Hanzawaia concentrica* (Cushman), which is generally thought to be indicative of mid-shelf to outer shelf environments.

31. An important aspect of Unit D is the occurrence of interspersed layers of poorly sorted sand, gravel, and pebbles in otherwise fine sand. Possible sources of this coarse material are a ridge-like feature of fine to coarse sand and gravel that lies at the toe of the shoreface in about 20 m (65 ft) of water or, most likely, adjacent beach deposits.

32. Unit E. Unit E, characterized by beach and dune deposits, consists of an uninterrupted section of up to 18.3 m (60 ft) of clean sand with gravelly layers in places. Typically, this unit is light gray (Munsell 10YR/4) and contains shell fragments, sparse foraminifera, and glauconite pellets. Mica is uncommon. The foraminiferal assemblage is dominated by *Elphidium*

excavatum (Terquem), with minor amounts of *Elphidium mexicanum* (Kornfeld), *Hanzawaia concentrica* (Cushman), and *Nonionella atlantica* Cushman.

33. A noteworthy feature of this unit is that it consists of an unbroken accumulation of over 18.3 m (60 ft) of apparent beach and dune sediments. This feature contrasts with that of many Atlantic Coast barriers where backbarrier sediments underlie the surficial beach and dune sands at comparatively shallow depths. Such sequences are the result of barrier retreat over the backbarrier deposits in response to rising sea level and storm wave attack. The only backbarrier sediments below the FRF site lie at more than 15.2 m (50 ft) below present sea level and were apparently formed during the late Wisconsinan or shortly after the site was inundated by the transgressing Holocene sea. Since initial deposition of Unit E commenced, there has been apparently little or no retreat of the barrier. A deposit of this type could also have been produced by inlet processes; however, there is no evidence of a former inlet in this locality.

34. Boring D2 (Figure 3) is representative of all but the offshore surficial sediments and is used here as a typical section; consequently, all available samples from this boring were analyzed (Figure 4*). Only selected samples of the other borings and offshore cores (Figure 5) were similarly analyzed. Most of these are of the lower, more complex sections. Size data were determined using a fall velocity sediment analyzer and thus represent effective hydraulic diameter rather than actual physical size. Gaps in the lower parts of the size plots (Figure 4) correspond to occurrences of peat or very silty sands which are not suitable for analysis by this method.

Offshore Morphology and Sediments

35. Data on the shoreface and inner continental shelf off the FRF site were obtained in 1980 as part of the Atlantic Remote Sensing Land-Ocean Experiment (ARSLOE). The collected data include seismic reflection profiles, bathymetric measurements, side-scan sonographs, and surficial sediment samples. This section is based largely on interpretation and reports of ARSLOE data in Williams (1983) and Meisburger and Williams (1987).

* To convert feet to metres use a conversion factor of 0.3048.

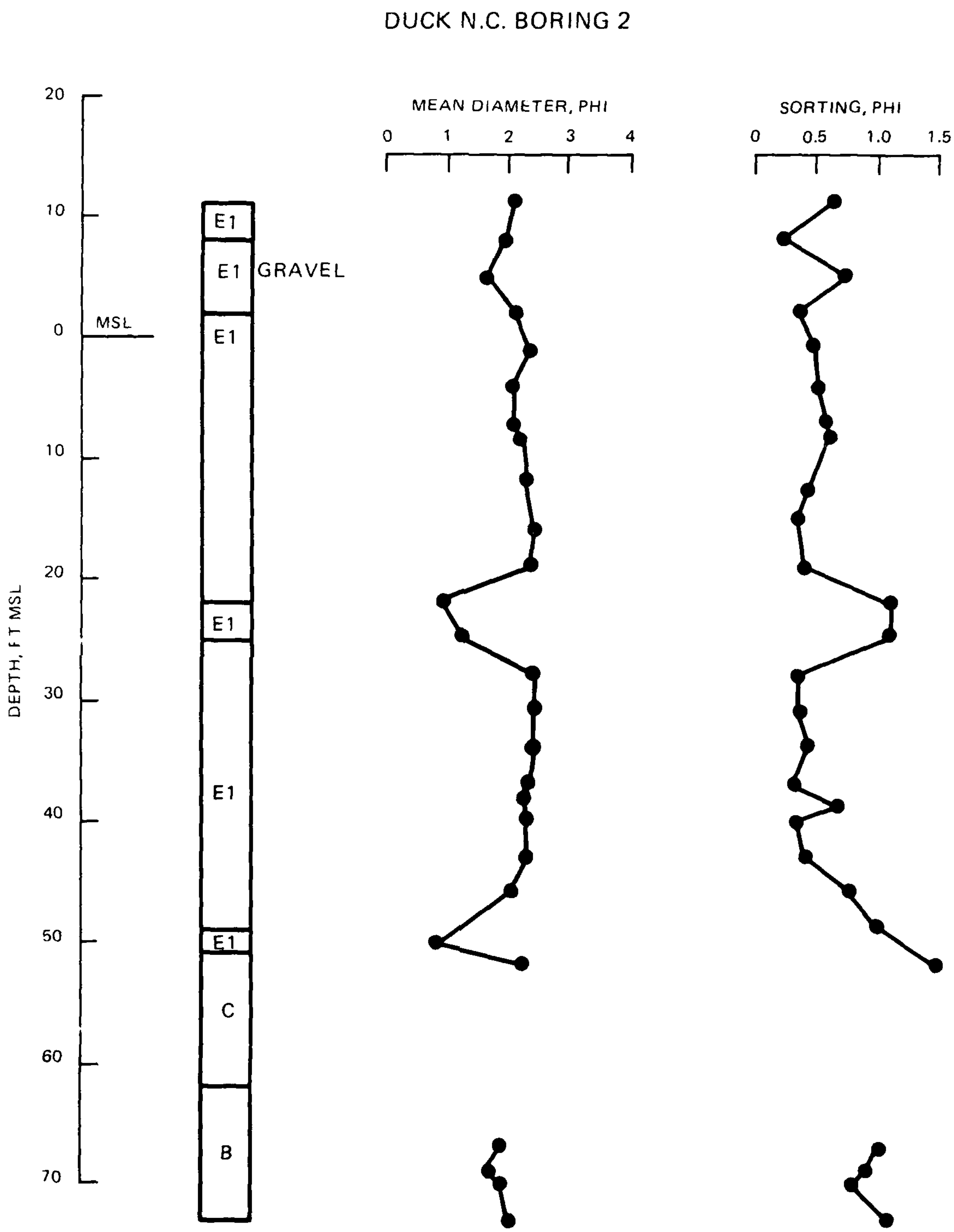

Figure 4. Sediment unit distribution, mean grain size, and sorting for Boring 2 (number 1 following unit designation denotes gravelly facies)

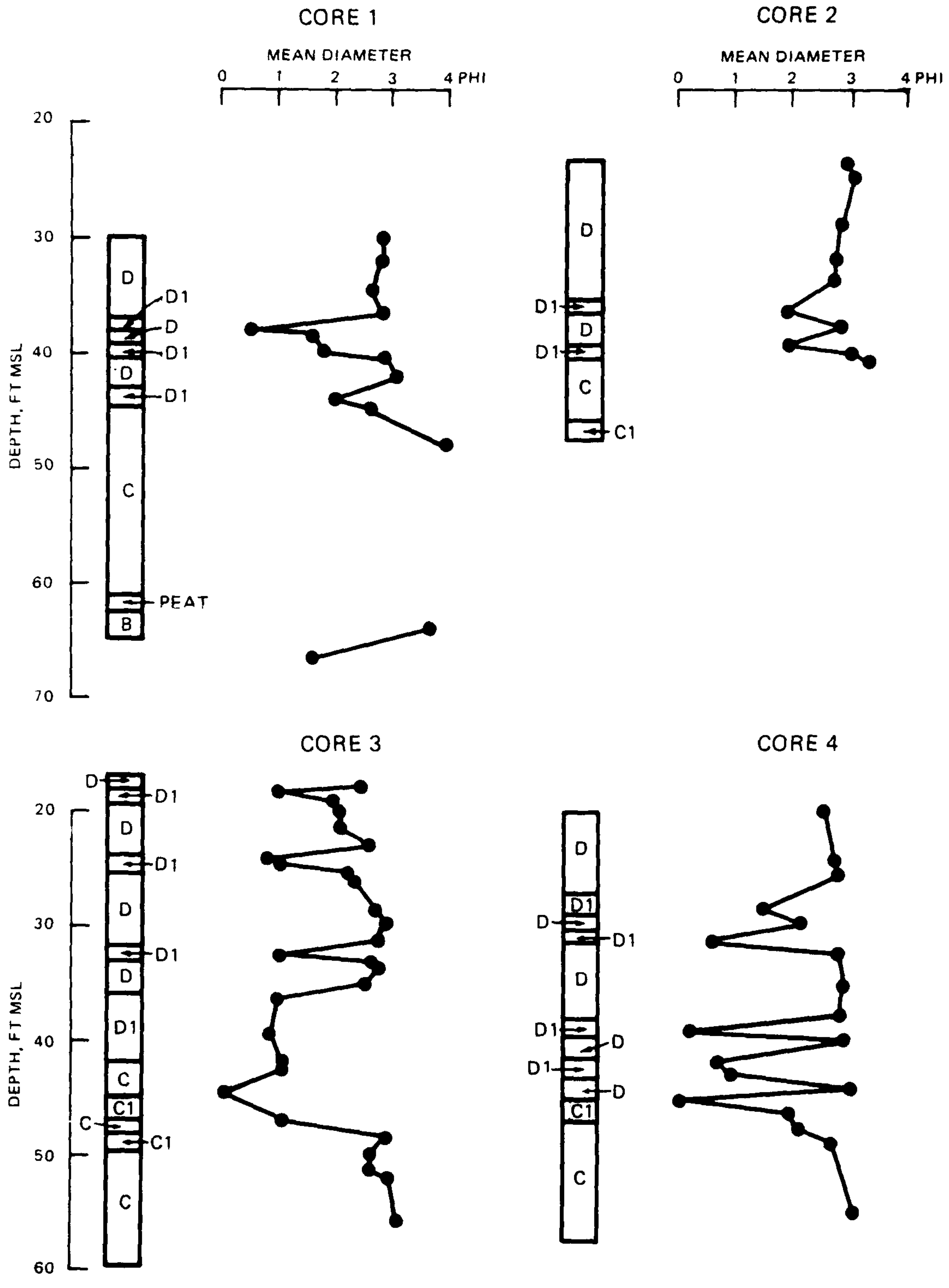

Figure 5. Sediment unit distribution and mean grain sizes for the nearshore cores

Morphology

36. Figure 6 shows the location of the ARSLOE transect off the FRF site. The profile in Figure 7 illustrates the irregular topography characteristics of the inner shelf with four large shoals occurring along the 37-km

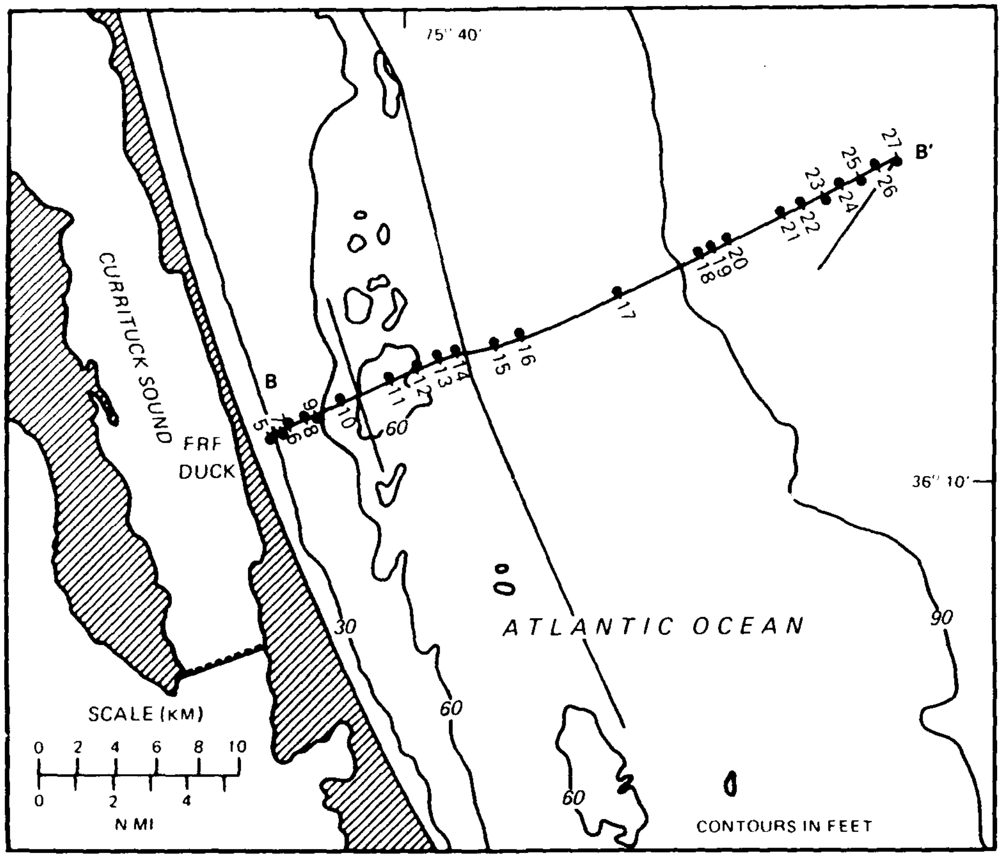

Figure 6. ARSLOE transect off the FRF site showing grab sample stations

(23.0-mile) length of the transect. These prominent shoals, designated A, B, C, and D (Figure 7), are up to 6 km (3.7 miles) wide and have a maximum relief of 3 to 6 m (9.8 to 19.7 ft). The shoreface is relatively steep and extends about 5 km (3.1 miles) offshore to a depth of 20 m.

37. Side-scan sonographs along the transect show the presence of bedforms consisting mostly of megaripples, the fairly straight crests of which are oriented north to north 20° E and crest to crest spacing of 1 to 2 m (3.3 to 6.6 ft). The megaripples have a patchy distribution. They are most common and best developed on the seaward flanks of the shoals where sediment grain sizes are in the medium and coarse sand range. Presence of bedforms as

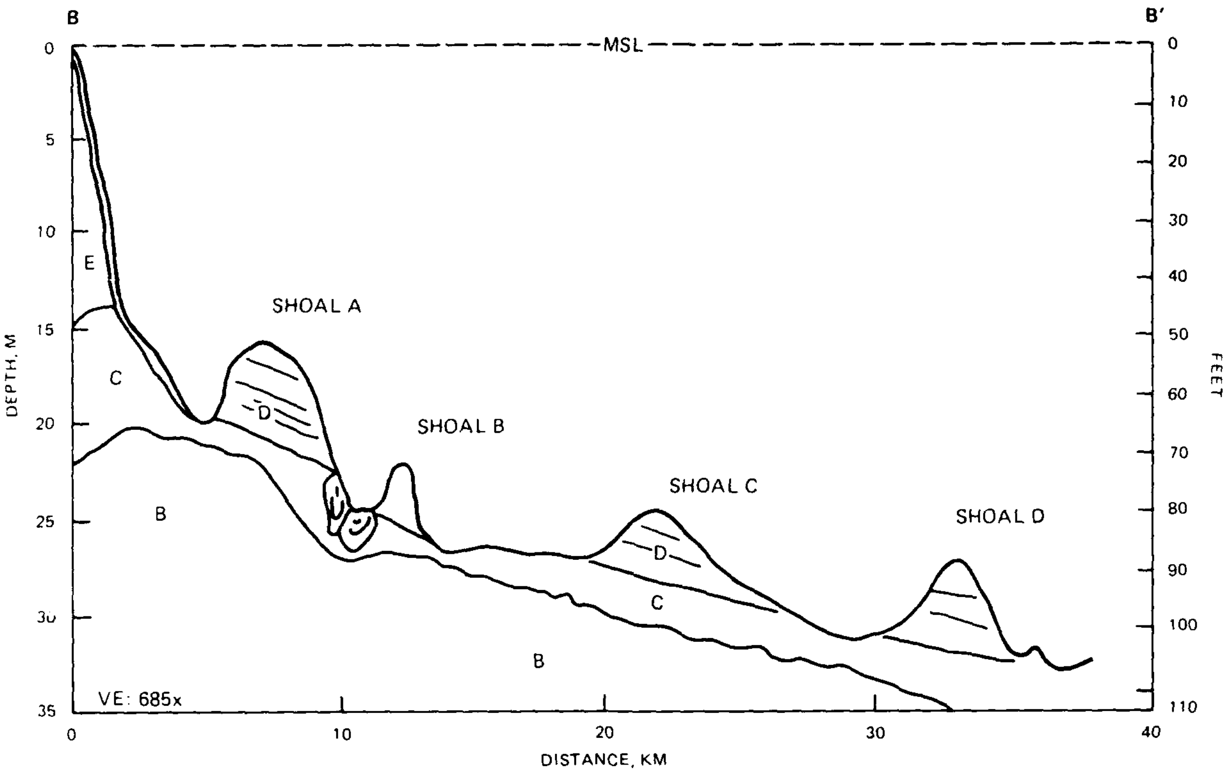

Figure 7. Profile showing the configuration of the shoreface and inner shelf along the ARSLOE transect (letters refer to sediment units)

far seaward as shoal D indicates that the shoals are probably affected periodically by currents and possibly reworked by storm-generated waves.

Offshore Sediments

38. Twenty-three grab samples were taken along the transect off the FRF site (Figure 6). Sediments along the transect are predominantly quartz sand; shells and shell fragments are common in places. Mean grain diameters range from very fine sand (0.063 to 0.125mm) to coarse sand (0.5 to 1.0mm) on the Wentworth scale; however, most samples are in the fine sand (0.125-0.250mm) category.

39. Heavy minerals are relatively common in the shelf samples and vary from 1 to 5.2 percent by weight in most samples; higher values of 7.7 and 21.1 percent were found in samples 20 and 19, respectively. Principal nonopaque heavy minerals were identified, and their percent frequency was determined (Table 3). the species of opaque heavy minerals were not identified, but their frequency as a group was determined.

Table 3

Minerals in ARSLOE Samples

Sample	Water depth, m	Percent Frequency: Zircon	Rutile	Garnet	Staurolite	Kyanite	Epidote	Hypersthene	Sillimanite	Amphibole	Tourmaline	Opaques to nonopaques, %	Mica to nonopaques, %	Glauconite per 0.15, gm	Mean diameter, mm	Heavy minerals, %
AR5	12.0			5.1	5.1	0.0	6.8			76.1	6.8	3.28	68.78	80.00	0.13	1.5
6	14.0			9.8	2.0	0.5	10.2	0.5		69.8	7.3	8.48	29.64	52.06	0.12	1.5
7	15.2			11.0	4.4	0.4	7.0		0.4	72.4	4.4	9.16	18.57	62.14	0.12	4.5
8	16.8			13.3	1.9		7.6			69.5	7.6	20.45	56.79	39.71	0.11	3.9
9	17.4			4.6	1.7	0.6	6.9		0.6	80.0	5.7	1.13	10.71	72.9	0.14	3.3
10	20.7			8.0	3.9		9.0	1.0		69.5	8.7	5.76	0.64	48.8	0.21	1.1
11	18.0		0.3	15.8	2.7	1.6	13.1	1.6	0.3	58.3	6.3	11.57	1.87	24.64	0.26	3.1
12	20.1			17.3	1.3		14.2	0.9		60.4	6.0	16.75	0.31	11.47	0.23	1.2
13	25.6	0.4		30.4	4.8	0.4	6.6	1.3		51.1	3.5	32.73	9.31	35.56	0.17	5.2
14	23.0	1.2	0.3	31.2	9.8	1.2	16.0	1.8		36.2	2.4	56.06		18.21	0.57	1.0
15	27.4			5.7	3.0	1.5	4.6	0.4	0.8	77.9	6.1	5.40	21.26	57.30	0.15	1.5
16	27.4			7.9	3.2		6.4		0.7	75.7	6.1	12.77	16.17	67.5	0.14	5.2
17	28.0			3.1	2.6	0.4	4.8	0.4	0.4	83.7	4.4	0.44	15.30	87.3	0.15	1.9
18	29.9			40.8	5.2	1.4	5.7	2.3	0.3	41.1	2.9	34.03	2.60	35.5	0.20	3.2
19	30.2	1.5	1.1	65.5	4.0	0.4	1.8	1.1		24.0	1.1	49.26	0.36	10.71	0.28	21.1
20	30.5			44.7	1.9	0.2	9.8	0.5		40.4	2.4	20.23	0.48	40.0	0.19	7.7
21	29.6			8.5	3.1	0.6	12.7	1.4	0.3	68.3	5.1	4.59	0.28	25.56	0.18	1.9
22	27.4			11.7	2.3		6.5	0.7	0.3	71.0	7.5	4.06		33.75	0.20	1.9
23	28.3			16.1	5.4	1.5	7.3	1.5		62.0	6.3	27.56	3.76	33.7	0.22	2.0
24	33.8			29.8	2.9		6.1	1.0	0.6	54.5	5.1	16.58	0.95	49.1	0.23	1.9
25	33.2		0.3	23.7	2.7		5.3	0.3	0.3	58.3	9.8	16.95	0.58	51.00	0.18	3.8
26	32.0		0.3	38.1			7.4	3.0		46.3	4.9	19.44	0.27	16.07	0.20	2.5
27	32.9			9.2	0.6	0.3	5.6	3.0	0.6	75.4	5.3	0.12	0.30	16.1	0.17	4.0

40. Only ten nonopaque heavy minerals occurred with regularity and with a frequency of 0.1 percent or higher. Only half of these (garnet, staurolite, epidote, amphiboles, and tourmaline) are common and occur at a frequency of 2 percent or more. Frequency distribution of the various heavy mineral species is irregular, but some broad trends can be recognized. Comparatively high garnet and black opaque values and a concomitant decrease of amphiboles occur in three groups of adjacent samples: (a) 13 and 14; (b) 18, 19, and 20; and (c) 24, 25, and 26. Frequency differences, however, are within ranges observed in samples from beach transects (Flores and Shideler 1982 and Meisburger (in preparation)) and thus may be the product of selective sorting rather than differences in source.

41. The percentage of mica to total nonopaque minerals plus mica is also included in Table 3. This easily eroded and transported mineral occurs in relatively high concentrations in samples 5 through 9 on the shoreface and samples 15, 16, and 17 from the flat area between shoals B and C (Figure 6). These samples contain the finest sediment along the transect. This relationship is consistent with the tendency of mica to be associated with sediments of finer grain size. The thin, flat shape of mica particles retards settling, producing an effective hydraulic diameter usually comparable to considerably finer material.

42. Glauconite pellets are present in all ARSLOE transect grab samples (Table 3). The glauconite pellets are, for the most part, medium green to nearly black and have a rounded or lobate form. Cracks filled with a granular material of white to pale green are common features. They are most abundant on the shoreface and in the flat between shoals B and C and thus show a distribution similar to that of mica. This occurrence suggests that the glauconite grains are detrital elements which did not form in situ.

43. Foraminifera are common secondary elements in the ARSLOE samples. Table 4 lists the percent frequency of the main foraminiferal species found. The dominant type in all samples is *Elphidium excavatum* (Terquem) which ranges in abundance from 64.4 to 96.9 percent of the total fauna. Other species present in most places in substantial numbers are *Eggerella advena* (Cushman), *Hanzawaia concentrica* (Cushman) *Proteonina atlantica* (Cushman) and *Quinqueloculina seminula* (Linné). *Proteonina atlantica* is listed separately in Table 4 because the tests of this species contained sufficient heavy minerals, so that most were not floated off with the other species in the

Table 4

Percent Frequency of Foraminifera in ARSLOE Samples

ARSLOE Sample Nos.	*Ammonia beccarii* (Linné)	*Bulimina* spp.	*Bucella hannai* (Phleger and Parker)	*Eggerella advena* (Cushman)	*Elphidium excavatum* (Terquem)	*Elphidium mexicanum* Kornfeld	*Guttulina* spp.	*Hanzawaia concentrica* (Cushman)	*Haynesina germanica* (Ehrenberg)	*Nonionella atlantica* (Cushman)	*Quinqueloculina seminula* (Linné)	*Rosalina* spp.	*Trochammina lobata* (Cushman)	Approx. % of *Proteonina atlantica* to all other types
5	1.0		1.4	0.7	90.4	2.7	1.0	1.0	0.3	0.3	0.3	0.3	0.3	0
6	0.4		0.8	6.5	87.5	0.8	0.8	1.14		0.8	0.8	0.4		0
7	0.3	0.6		0.8	96.9	1.1	0.3	0.6				0.3		0
8		0.3	1.0	3.6	92.9	1.3		0.32						0
9	1.0		2.9	2.4	89.4	0.5		2.9			1.0			0
10	1.5		4.4	2.9	64.4	2.9	2.6	13.23			7.4		0.6	0
11	2.0		1.6	0.41	69.6	0.8	4.0	13.4		0.4	7.5			0
12	4.7		3.7	0.3	71.9	0.7	1.0	9.4	0.3	1.0	6.7		0.3	11.1
13	2.9	0.3	2.0	0.3	88.2	0.3		4.0		0.7	0.7	0.7		30.0
14					not enough specimens for count									
15	0.4	1.2	2.6	5.7	85.1	1.6	0.4	1.0	0.6		0.4	0.8	0.2	32.4
16		0.9	1.5	0.3	90.5	0.3	0.9	3.0	0.6		1.8	0.3		25.9
17	1.4	1.0		17.4	68.6	0.7		5.1		0.3	0.3			28.1
18	2.0	1.4	1.7	0.7	79.4	1.0	2.4	7.8	0.7		1.4	1.0	0.3	14.3
19	0.6	0.3	0.3	0.9	89.7	1.7	0.6	4.3	0.3				0.9	13.3
20	1.2	2.4	2.7	8.1	79.7		1.8	1.8	1.2				0.3	16.0
21	0.4	0.4	1.8	5.0	68.5	1.1	2.5	10.4	1.8	1.4	5.3	0.7	0.7	52.0
22	0.7	0.7	2.1	1.0	80.0	0.7	3.1	7.6	0.7	0.3	2.8		1.0	23.8
23	1.9	0.7	0.4	1.9	66.3		1.9	14.1	1.1	0.4	7.8	1.9	1.9	0
24	2.3	0.3	1.0	2.7	78.9		0.7	10.2	1.0		4.6			10.0
25	0.3		0.7	1.4	86.9		1.0	3.4	2.1	1.0	0.7		0.3	22.2
26	0.2	1.1	1.7	0.8	77.8			7.1	4.1	0.2	2.4	0.2	2.8	26.1
27	1.4	1.4	0.7	3.6	74.3			10.1	4.4	0.2	0.4		0.4	36.7

separation process; consequently, they were counted in unseparated sample material. Because foraminifera are sparse in the unseparated material, a relatively small number of specimens were counted; thus the listed frequency of *Proteonina atlantica* is approximate.

44. Variations in frequency of foraminiferal species along the transect are not generally pronounced; however some trends do occur. The strongest trend is the absence of *Proteonina atlantica* shoreward of sample 11 and its presence in substantial numbers from sample 12 to the seaward end of the transect. On the shoreface (samples 5 through 9) *Elphidium excavatum* is abundant, while *Hanzawaia concentrica* and *Quinqueloculina seminula* are relatively sparse. The latter two species increase seaward of the shoreface and reach their greatest abundance on shoals A and D.

PART IV: SUMMARY

45. CERC's FRF is located on the northern part of the Outer Banks of North Carolina. The Outer Banks consist of a series of relatively narrow barrier islands backed by broad, shallow sounds. The islands form the seaward margin of the Atlantic Coastal Plain in this region which is mantled by rock units ranging from Cretaceous to Holocene Age. It gives way inland to the Piedmont Province which is composed of more resistant and complex rock units.

46. The origin of the Outer Banks is not precisely known. It appears likely, however, that they either initially formed seaward of their present location during the Holocene transgression or later by spit extension and segmentation from headlands of preexisting Pleistocene deposits.

47. During the past 130 years the shorelines of both the ocean and sound sides of the barriers have retreated in most places, resulting in narrowing of the islands. The average rate of ocean-side shoreline retreat during this period was 0.8 m (2.6 ft) per year. Average retreat rate on the sound side has been 0.1 m (0.33 ft) per year.

48. Engineering borings from the site of the FRF penetrated four distinct sediment units. The uppermost unit consists of barrier and dune sands that are more than 18.3 m (60 ft) thick. Below this section are two units of much finer-grained sediments underlain by a sand unit that, unlike overlying units, contains no mollusk shells, foraminifera, or other organic calcareous matter. The nonopaque heavy mineral assemblage of the units is similar. The most common minerals are amphibole, epidote, staurolite, tourmaline, and garnet. Epidote is significantly higher in the lowermost unit, suggesting possible source differences. Foraminifera occur in all but the lowermost unit. *Elphidium excavatum* (Terquem) dominates the assembly with a frequency of over 90 percent occurrence.

49. The inner continental shelf along a 37-km transect off the FRF is irregular with four broad shoals interrupting the gentle seaward inclination of the shelf floor. Side-scan sonographs show the local presence of megaripples. They are particularly common on seaward flanks of the shoals.

50. Surficial sediments along the 37-km transect are predominantly very fine to coarse quartz sand. Heavy minerals make up 1 to 21.1 percent of the material. The main nonopaque heavy mineral elements are garnet, staurolite, epidote, amphibole, and tourmaline. Mica and glauconite pellets occur in

shelf sediments and are most abundant on the shoreface and in the broad flat between shoals B and C.

51. Foraminifera are common along the shelf transect. The assemblage is dominated by *Elphidium excavatum* (Terquem) which makes up 64.4 to 96.9 percent of the fauna.

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